BIM to Numerical Modelling Interoperability for Geotechnical Design of Underground Metro Station

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ABSTRACT

Building Information Modelling (BIM) is one of the important processes being adopted by the construction industry as it provides a collaboration platform in conjunction with technical standards for interoperability over the lifecycle of an asset. However, geotechnical analysis engaging numerical tools has yet to leverage the BIM benefits due to the lack of effective interoperability means, which not only results in unnecessary remodelling and rework at a cost of labour and computational waste, but also with possibility of errors, misinterpretation and omission of information. Using a trinocular underground station as an example, a workflow underpinned by heuristic techniques is proposed to enhance the interoperability between a BIM design authoring tool (Revit) and a numerical modelling tool (FLAC3D) for geotechnical analysis. A BIM-based multiple LoD (levels of detail) model framework is proposed to represent different information requirements for different purposes of BIM use throughout the project lifecycle. Leveraging the associated geometry and semantics, techniques of parametric modelling, data manipulation via visual and traditional programming are engaged to bridge BIM and numerical modelling for geotechnical analysis on different design scenarios. The simulated results are visualised through a backward automation cycle to Revit for design optimisation. The presented solution offers and automates an error-free design-to-design workflow solution and therefore enables efficient exploration of design scenarios and design optimisation.

Keywords: Building Information Modelling (BIM), numerical modelling, automation, underground, metro station

1 INTRODUCTION

Building Information Modelling (BIM) is one of the important processes being adopted by the construction industry as it provides a collaboration platform in conjunction with technical standards for interoperability over the lifecycle of an asset (Azhar, 2011; Gu and London, 2010). While many analyses are now performed in computational environments capable of 3D representation and object-based design, there remain limitations of model-based collaboration and multidisciplinary integration in the underground construction processes, such that activities of disciplinary analyses are still performed in non-BIM environment, for example spatial coordination of geological model and infrastructure model often conducted in geographical information system (GIS) and structural analysis in numerical modelling programs (Huang et al., 2021). One important process often being excluded from the BIM environment while bearing significance to engineering success of underground construction is the geotechnical assessment based on analytical, empirical or numerical models. Heterogeneous applications are often used to complete this task without referencing to the BIM model that is supposedly the single source of information. This inadequately coordinated workflow not only results in the iterative, manual retrofitting with high labour and computational cost, but also inherits great risks of misinterpretation and omission of information (Ninic, 2021). Therefore, this paper proposes to build a link between BIM and numerical modelling to enable the prediction of geomechanical consequences of design variations via the parametric BIM modelling, parameter visualisation and optimisation, and programming. This paper focuses on improving interoperability between BIM design authoring and numerical simulation-based geotechnical analysis for an underground station from several perspectives, including identification of the information requirements on the exchange scenario of BIM design to numerical simulation for geotechnical analysis of underground station, the development of a multi-level BIM parametric station model considering the varying richness of information requirements, and the innovation of an intermediary solution based on automating information interchange workflow between design and numerical simulation for geotechnical analysis.

2 RELATED STUDIES

This section provides a brief literature review on aspects of information modelling in underground construction, multi-arch cavern design, stability analysis and existing interoperability efforts of information and numerical modelling.

Information modelling platforms developed with a modular or layered structure have been proposed in existing research (Huang et al., 2021, Koch et al. 2017, Zhu et al., 2017). The importance of geological and geotechnical information is well understood for underground construction design. However, much of this data is either proprietary or stored in formats requiring specific software to view. In order to make such information more accessible for future project planning and preliminary-stage design, some online infrastructures are built that allow public to interactively search, view and use borehole data according to their geolocations. Figure 1 illustrates an example of this type of platforms using the “Data and Information on the Dutch Subsurface (DINOloket Netherlands, 2019)”. With the increasing accuracy and data type coverage, future engineering design for underground construction could better leverage the open-source geological and geotechnical data.

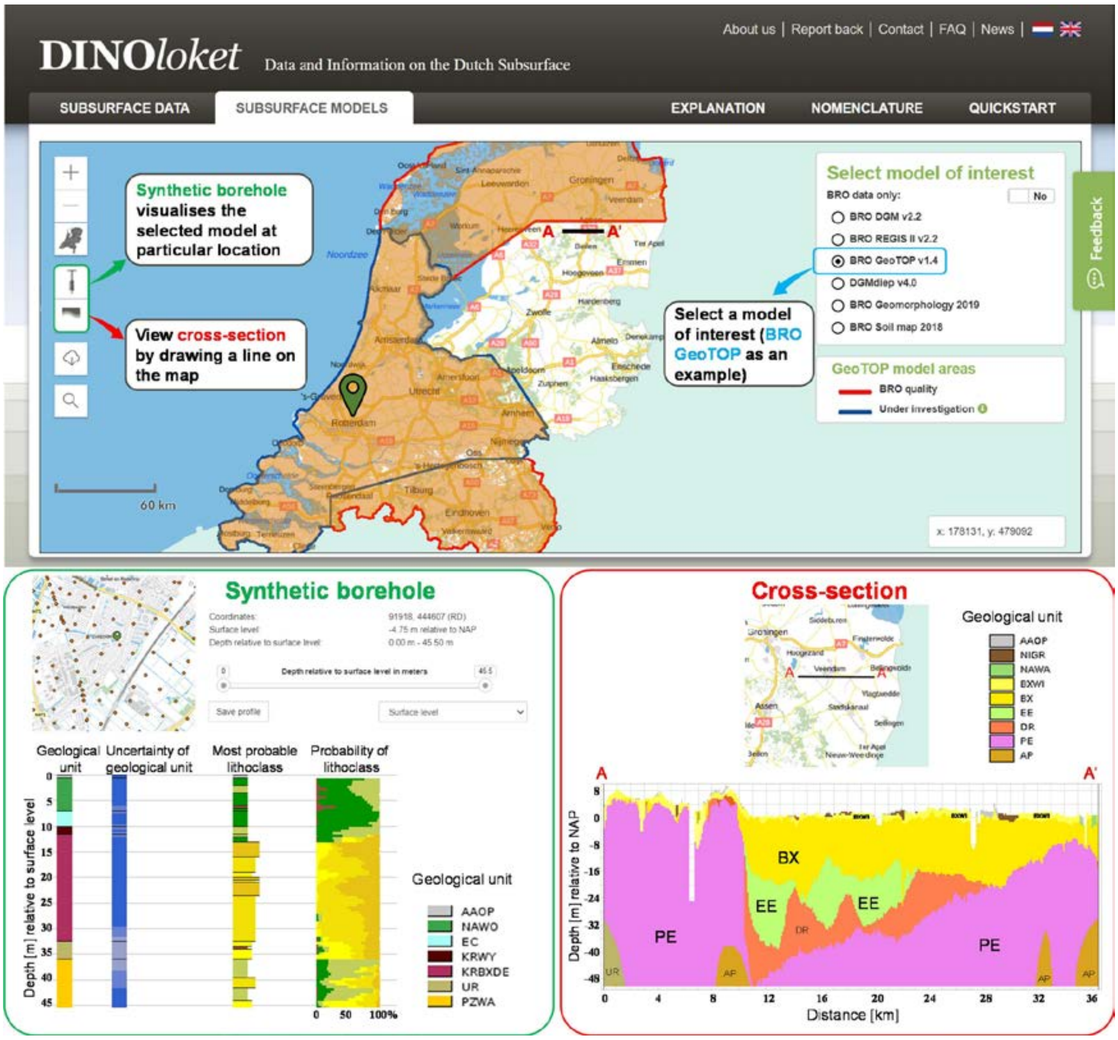


Figure 1. Demonstration of creating synthetic borehole and cross-section (Top: the main interface for user inputs including selection of model of interest, locating synthetic borehole and viewing custom-defined cross-section; bottom left: the resulted information of synthetic borehole including relevant geographical and geological data; bottom right: the cross-sectional geological information). (Huang et al., 2021)

A multi-arch cavern is a common structure adopted for underground metro stations with columns and walls providing support to the wide-span. Examples of stations using such structure include Moscow Mayakovskaya station (Shilin et al., 2016), Tokyo Kiyosumi-shirakawa Station (Konda, 2003), and Beijing Badaling Great Wall station (Li et al., 2020). Figure 2 illustrates an example of typical triple arched cavern and support systems. The construction methods or philosophies, such as sequential excavation method (SEM), sprayed concrete lining (SCL), New Austrian Tunnelling Method (NATM), and the 'Analysis of the Controlled Deformation in Rocks and Soils (ADECO-RS)' emphasised the significance of excavation and construction with adequate observation and support measures. The components prescribed in these methods should be modelled. Their mechanical properties should be taken care of given the information modelling approach is undertaken.

The stability analysis of the cavern structure is essential to geotechnical engineering. With computer software and information technology becoming easily accessible, numerical modelling methods such as the Finite Element Method (FEM), Finite Difference Method (FDM) and Discrete Element Method (DEM) have been used as common means to simulate different engineering scenarios of underground excavation and structure short-term to long-term stability. Since BIM models consist of geometry and semantics, BIM could act as a pre-modeller and post-viewer for numerical modelling, the BIM-numerical modelling interoperability, therefore, allows an error-free exchange of information between the two interfaces.

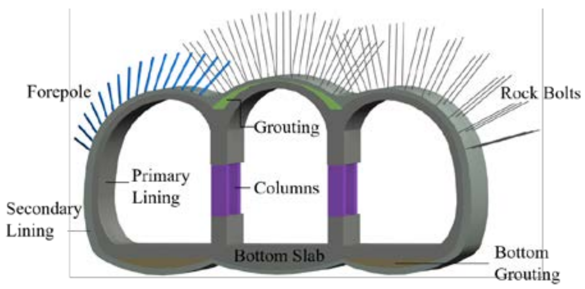


Figure 2. Example of a typical triple-arched cavern and support systems.

BIM encompasses a set of tools, technologies and processes ranging from parametric modelling (Ninic et al.,

2021) to project lifecycle management (Wang and Zhang, 2021) that are driving the digital transition of the Architecture, Engineering and Construction (AEC) industries. Many of the benefits suggested by adopting BIM and digital information technologies, such as improved visualisation and cross-disciplinary communication and collaboration, are desired for underground construction. For example, the downstream application of BIM has been investigated for tunnels. In Ninić et al.(2018, 2020 a and b), BIM-to-FEM and BIM-to-IGA workflows were developed, incorporating machine learning techniques, to deliver solutions that focus on automating model generation and simulation for numerical analysis on shield tunnelling induced settlement and decision aid on parameter optimisation in soil condition. Fabozzi et al. (2021) has also studied BIM-to-FEM and FEM-to-BIM interoperability via the use of several software tools, including commercially available rail design modelling package.

The existing research demonstrates the necessity and achievement to date of BIM uses in underground construction and solutions of bridging information modelling and numerical modelling. Nevertheless, the outlined prototypes and modelling methods have yet been generalised to facilitate the information modelling of all underground space usages. Besides, among those considered the interoperability between the information and numerical modelling, the engaged software tools may not have the built-in constitutive models to characterise the materials that make up the model or not necessarily capable of representing the large deformation of wide-span cavern structure. More specially, the workflow of Ninić et al focuses on circular tunnel in soil conditions, indicating relatively simple geometrical efforts and singular support structure (lining) involved in both BIM and numerical modelling process, and the specific meshing tool (GiD) and the research-oriented open-source simulation software program (Kratos) are engaged. Whereas the solution proposed by Fabozzi et al. (2021) is based on use of a commercialised software suite designed for railway, which could be leveraged for analyses in similar condition but may lack the versatility given that the required design or analysis exceeds the capability of the software packages.

This paper is therefore founded on the need of examining solutions to enhance interoperability between BIM authoring tool and numerical modelling software codes that are particularly suitable for cavern stability problems.

3 METHODOLOGY

Using a tri-arch underground station as an example, the information exchange between two main interfaces investigated in this paper are Revit and FLAC3D. A tri-arch station BIM model will be established under the multiple levels-of-detail (LoD) framework that intents to represent the different information requirements for the BIM model throughout the lifecycle of the construction. Leveraging the associated semantics, data mapping and parameterisation is achieved via visual programming, which also facilitates visualisation of numerical results back in the BIM environment. The two-way workflow was automated via the use of Python interface. Figure 3 illustrates the proposed workflow, which incorporates BIM-based alignment selection, visual programming generating parametric station models along with other project data to feed the exchange enabler and to allow setting of meshing parameters, initial and boundary conditions, and excavation and ground support properties.

3.1 Multi-LoD station BIM

The station model adopts the concept of “Level of Detail (LoD)”, which specifies what objects are included in the model and the degree of detail with which each object is modelled (Sacks, 2018).

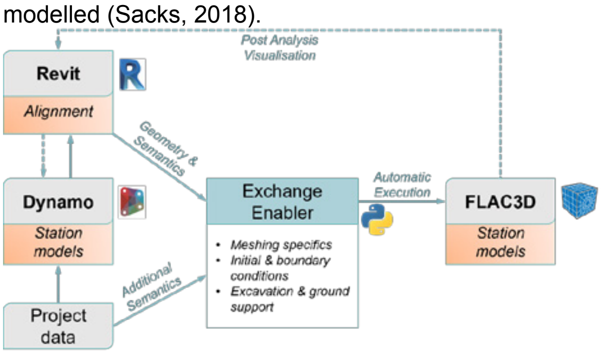


Figure 3. Workflow proposed in this paper

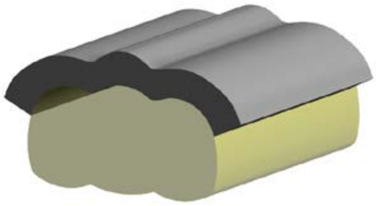
The LoD required for 3D modelling varies depending on the specific BIM goals and the types of model used throughout the project’s lifecycle. The modelling process for any large infrastructure project, such as erecting a skyscraper in the urban centre, or constructing a train tunnel running between opposite ends of a city, often involves structures with widely differing scales, geometric appearances, and spatial arrangements. Therefore, it requires the participating engineers and designers to define carefully the LoDs for the to-be-modelled objects in order to address this peculiarity of infrastructure design.

Figure 4. demonstrates examples of a triple-arch station model with different LoD emphasising the variation of model content in terms of excavation support. At a low level of detail, it mainly includes the spatial illustration of excavation support means such as the major primary and secondary support while the high LoD-model includes physical elements of the primary (e.g. forepoling and rock bolts) and secondary support (e.g. cast-in-place concrete lining). In this study a LoD300 model is adopted for the use case of geotechnical analysis.

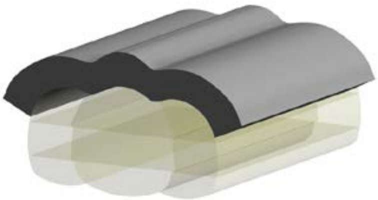
3.2 Parametric modelling

From a historical perspective, BIM model generation and design technology are evolved and matured based on 3D solid modelling, which represents the ability to generate and revise arbitrary 3D solid, and reaching its climax in object-oriented parametric geometry modelling. The then-state-of-art method integrated two forms of 3D solid modelling techniques, namely the boundary representation (B-rep) and the Constructive Solid Geometry (CSG), to realise functions of editing, visualising, measuring, clash detection as well as other non-editing uses (Sacks, 2018). Thereafter, the solid modelling computer-aided design (CAD) systems were improved by recognising the connectivity of shapes through sharing parameters and building links. Eventually, the realisation of automatic update and rebuilt of shapes via parametric relations marked the era of parametric geometry modelling.

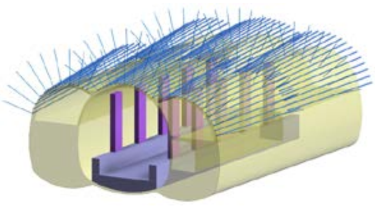
Parametric modelling is adopted for reusability and extensibility, which refers to establishing intelligent objects and object assemblies described with parameters. The to-be proposed methodology largely relies on computational design concepts, which have been in use for architectural designs since emerging in the 60s, and has more or less influenced the development of BIM tools. Both parametric design and generative design are popular terms considered in the scope of computational design (Caetano et al., 2020). Establishing a component (referred to as a family in the selected BIM software), for example a bolt, based on constraints of parameters and rules denotes parametric design for a single element.



(a) LoD 100



(b) LoD 200



(c) LoD 300

Figure 4. A triple-arch station model with LoD 100 to LoD 300 (construction sequence and support systems are modelled)

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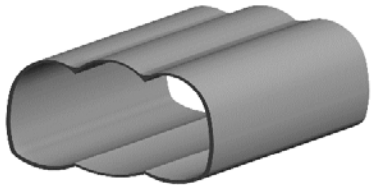
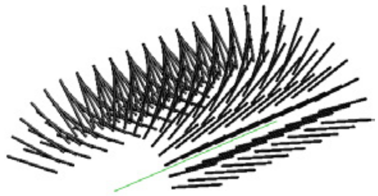
BIM applications and BIM enabled platforms usually provide an extensive set of predefined parametric object classes and families while allowing users to customise when a desired parametric object does not exist in the specific BIM tool. However, underground infrastructure such as the metro station often do not reflect the target functionality of most BIM tools designed for architectural and building modelling, constructing custom parametric objects and families is inevitable. Several design-based parametric families are created for this study, mainly concerning the geotechnical analysis that will be performed. Example of an outer shell and rock bolts as forms of excavation support are illustrated in Figure 5. The triple arched primary lining as the outer shell is essentially created by extrusion, which is a simple parametric modelling procedure.



(a) Primary Lining



(b) Rock Bolts

Figure 5. (a) Primary lining family as a type of support and(b) assembly of rock bolt family instances.

Then, we propose to use computational design approach in conjunction with parametric modelling and visual programming to account for assembly and construction constraints. This approach holistically considers the elements and variations of elements implying regional geological conditions, excavation sequence and support installation, so that design flexibility and convenience of modification and retrofit can be achieved. Figure 6 illustrates the layout of visual programming procedures engaged to create a station model ready for geotechnical analysis.

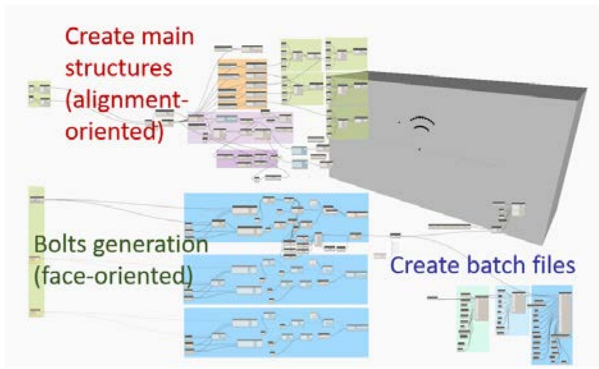


Figure 6. visual programming layout of instantiating lining, ground and rock bolts (controlled by alignment and faces) and generation of batch files for numerical simulation.

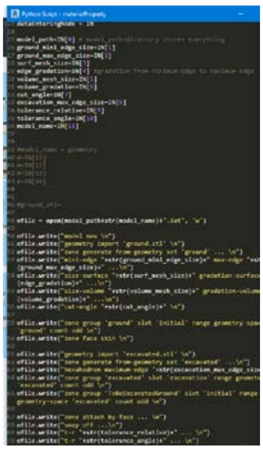
3.3 Model semantic enrichment

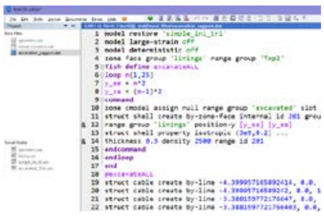
As aforementioned, geological and geotechnical quantification is of paramount importance to numerical simulation for ground stability analysis. The process of assigning or embedding related attributes in the geometries is regarded as semantic enrichment in BIM. In this study, we dedicated another visual programming algorithm to achieve this goal. The stored parameters for a rock bolt as an example could include density, grout-cohesion, grout-friction, grout-stiffness, yield-compression, yield-tension, and young's modulus. These properties are then read and input by Python script into numerical simulation program to perform calculation concerning geotechnical problems such as ground settlement, structural deformation and yielding.

3.4 Information exchange and process execution

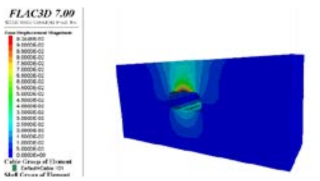
The interface selected for numerical simulation for geotechnical analysis is FLAC3D, which supports a command-driven program execution and allows the use of data files (.dat format) to describe the model (Itasca, 2019). This supposedly outdated program design is actually favoured in information exchange scenarios as it makes the complete automation of program execution possible.

An exchange enabler is proposed to facilitate exchange of BIM model and automate the execution of numerical simulation. The enabler is realised by a set of Python scripts under a modular structure to allow future extensions and convenient modifications. The modules are constructed in accordance with the general solution procedure of the numerical modelling program. The processes of data file generation and process execution is illustrated in Figure 7.





(b) simulation execution



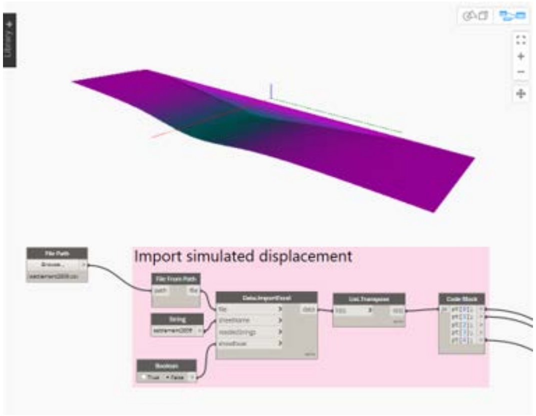
(a) exchanger (c) simulation result

Figure 7. (a) batch file generation enabled by the exchanger; (b) program execution and (c) simulation result plotted in the numerical simulation interface.

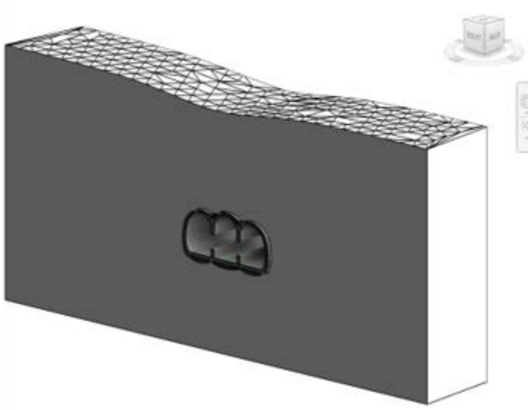
3.5 Results Visualisation

A back-analysis loop is enabled also through a dedicated algorithm to help visualise the impacts of underground construction in the BIM native environment. By combining the settlement effect with existing structures such as buildings, existing tunnels, or geological structures, design variations could be proposed and tested following the same procedure.

Both coloured contour and mesh distortion are achieved to visualise the settlement results obtained from numerical simulation. Since parametric modelling is used, parametric study could be easily facilitated by adapting, for example, the overburden thickness, station cavern shape, lining thickness and installation pattern of ground support systems.



(a)



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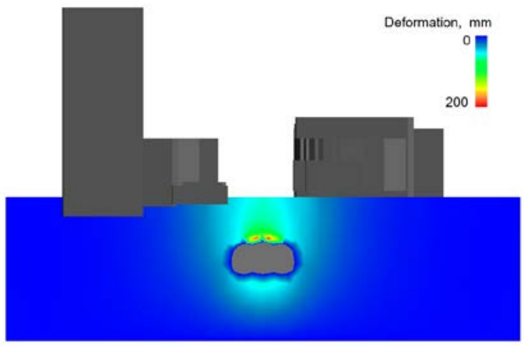

(c)

Figure 8. Visualisation with (a) contour coloured map in visual programming interface, (b)mesh distortion and (c) contour coloured map illustrating deformation of a cross-section via cutting plane perpendicular to the triple-arch cavern.

4 DISCUSSION

The workflow consisted of three parts: (1) generation of structural model of underground metro station encompassing both geometries and semantics via parametric modelling and visual programming; (2) automation of model exchange and calculation commanding by python scripts; and (3) development of a reverse loop to visualise numerical calculation results in BIM environment for further analysis, parameter optimisation and scenario refitting. The workflow is marked by its modularity and extensibility that could be easily adapted for further development. Each part is valid as a single system while creating an efficient BIM-to-numerical modelling loop for geotechnical analysis. Currently, the exchange module is developed for the specific interfaces that it is connecting, this means that certain adaptations are required if other software tools are employed for BIM and numerical simulation. Another limitation the current exchange module may suffer from is the level of complexity in meshing. The success of FEM or FDM simulation largely relies on the quality of meshes while examples used to testify the workflow have only involved relatively simple geometrical structures without comprehensive set of interfaces. A potential approach that would be investigated in the next stage is to engage a meshing program as a middle-ware or to experiment with the octree mesh in FLAC3D. Ultimately, proper translators could be developed based on BIM data schema, such as the industry foundation class (IFC). There is yet standard for underground construction based on IFC while research and development efforts are ongoing by buildingSMART, an international industry body aiming at improving interoperability between software applications used in the construction industry, cooperating with other organisations focusing on subsurface utilisation, such as the International Tunneling and Underground Space Association (ITA-AITES).

5 CONCLUSION

This study aims to provide a solution to tackle the problem of lacking open standard data models that cover the context-specific knowledge required for underground construction. By leveraging the parametric modelling technique of BIM, the workflow could mitigate the efforts of numerically retrofitting and re-modelling at feasibility and earlier design stage. The enabled a design-to-design workflow with the reversed visualisation loop creates opportunity for backanalysis and design optimisation.

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